THE NEW ENGLAND SEISMIC NETWORK

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Project Summary

The Massachusetts Institute of Technology and Boston College have collaboratively operated the New England Seismic Network (NESN). Locations and magnitudes of earthquakes recorded by the NESN are reported to public safety agencies and the public. Data dissemination tools are developed to rapidly deliver earthquake information in a high quality format on our web-sites. A periodically updated archive of digital ground-motion data is maintained on-line for easy access by the research community and other seismic networks via the Internet. Earthquake source properties, the effect of earth structure on ground motions in urban areas, and potential seismogenic structures are studied to characterize earthquake hazard in New England.

Investigations Undertaken

The Earth Resources Laboratory (ERL) of MIT and the Weston Observatory (WES) of Boston College operated jointly the New England Seismic Network (NESN). The objectives of the NESN are:

- to continuously monitor and report earthquakes to agencies responsible for public safety,
- to educate the public about seismic hazard by providing general and technical information about earthquakes,
- to use the recorded data to conduct seismological research aimed at reducing earthquake hazard in New England.

The results of investigations aimed at achieving the three objectives listed above are obtained through three main activities:

- Seismic Network Monitoring
- Data Management and Dissemination
- Seismic Hazard Research

Research Objectives and Results

SCATTERING AND ATTENUATION OF SEISMIC WAVES IN NORTHEASTERN NORTH AMERICA[1]

Abstract

The energy-flux model of seismic coda, developed by Frankel and Wennerberg (1987), is used to derive path-averaged estimates of scattering (Q_S^{-1}) and intrinsic attenuation (Q_I^{-1}) for northeastern North America. The model predicts the amplitude of the coda wave vs. time as a function of frequency, Q_S^{-1}, and Q_I^{-1}. A non-linear inversion scheme is developed that allows for the estimation of Q_S^{-1} and Q_I^{-1} as a function of frequency by fitting the model to a narrow-bandpass filtered envelope of the seismic coda for each seismogram at discrete frequency points. The inversion is performed on seismograms from earthquakes recorded by the MIT New England Seismic Network (NESN) over a 15-year period between 1981 and 1995. Preliminary results indicate that scattering is the dominant mechanism of energy dissipation, and that the effects of intrinsic attenuation are secondary. The scattering is strongest at shorter propagation distances and decreases substantially as the propagation distance increases. Conversely, intrinsic attenuation is negligible at shorter propagation distances and increases as the propagation distance increases. These results are interpreted as indicative of a strong scattering region at shallow depth, with the scattering decreasing with increasing depth, and with a subsequent increasing of intrinsic attenuation at greater depth. A second analysis is performed to invert the path-averaged estimates of Q_S^{-1} and Q_I^{-1}, using a constrained linear method with regularization, to obtain a one-dimensional depth model of $Q_S^{-1}(z)$ and $Q_I^{-1}(z)$ in the crust. These results indicate that the scattering is confined to the shallow part of the lithosphere and decreases rapidly with depth, while the intrinsic attenuation is negligible at the surface and increases with depth. Possible mechanisms for the scattering include the presence of a weathering layer near the surface, the presence of fractures in the shallow crust, and topography.

Introduction

The estimation of earthquake hazard in a particular area is a two-part process. First, an understanding of the nature of the earthquake sources that can produce potentially damaging ground shaking is required. This includes knowledge of the distribution of the seismic source regions, the magnitude and recurrence time of the earthquakes, and the nature of the earthquake source mechanism within each seismic region. Second, an understanding of the effect of the transmitting medium, i.e., the Earth, is also required.

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The transmitting medium is characterized by two parameters. The first of these is the seismic velocity, i.e., the velocity at which seismic waves travel through the medium. The seismic velocity depends both on the type of seismic wave and on the nature of the material through which the seismic waves propagate. In the Earth, seismic velocity varies predominantly as a function of depth, with smaller-scale velocity variations present in three dimensions. The second of these is the seismic attenuation, which is a measure of the loss of energy in the seismic waves. The attenuation of seismic energy consists of two parts; the dissipation of energy, usually referred to as intrinsic attenuation, and the scattering of energy due to small-scale heterogeneities in the Earth as a result of the three-dimensional velocity variations mentioned above.

Of the two medium parameters, the seismic velocity is easier to estimate. Seismic velocity depends on the travel times of the seismic waves, and travel-time measurements tend to be more robust than the amplitude measurements that are required for an estimation of the seismic attenuation. In fact, amplitude measurements often show great variability within a given seismic network, especially in the short-period range of 1-20 Hz of interest in this study (e.g., Chang and von Seggern, 1980).

The standard approach to the study of scattering and intrinsic attenuation at short periods (i.e., 1-20 Hz) and at regional distances (less than 300 km) is to use the amplitudes of the seismic coda waves. Coda waves are prominent in the latter part of regional seismograms and are assumed to consist of backscattered S-waves from randomly distributed heterogeneities in the Earth's lithosphere (Aki, 1969). An example of a regional seismogram showing a prominent seismic coda is shown in Figure 1. The seismic coda shows a characteristic exponential decrease in amplitude with increasing lapse time.

Many phenomenological models have been developed for the excitation of seismic coda waves. Sato and Fehler (1998) and Sato et al. (2002) give a comprehensive review of these models. These models can be classified into two categories; single-scattering models and multiple-scattering models. Single-scattering models assume that the scattering process only occurs once: in other words, once seismic waves have been scattered by heterogeneities in the Earth, they do not produce secondary scattering from other heterogeneities. This assumption is referred to as the Born approximation. Single-scattering models therefore work best where the scattering process is weak. For example, Aki and Chouet (1975) proposed such a model for a lithosphere with a homogeneous background velocity and a random distribution of point-like scatterers with co-located sources and receivers.

In contrast, multiple-scattering models are not restricted to the single-scattering mechanism and therefore have a wider range of application, especially in the case of strong scattering. Several different approaches have been used in the case of multiple scattering. Wesley (1965) and Dainty and Toksöz (1977) used diffusion theory to model scattering in a medium with randomly-distributed heterogeneities. Wu (1985) and Wu and Aki (1988) used radiative transfer theory to model scattering. Frankel and Wennerberg (1987) used an energy-flux approach to modeling scattering, where energy is transferred from the direct wave (i.e., the S-wave) to the scattered wave (i.e., the seismic coda).

In this study, the energy-flux model of Frankel and Wennerberg (1987) is used to estimate the scattering and intrinsic attenuation properties of the lithosphere in northeastern North America. This model has certain advantages, not only regarding the model itself, but with respect to the limitations of the seismic data used in the study.

Previous studies of the scattering and attenuation for this region were undertaken by Pulli (1984) and Toksöz et al. (1988). Pulli (1984) used a single-scattering model to estimate Q_C from the seismic coda of nine earthquakes in New England. The results of this study show that Q_C varies as a power-law function of frequency f and is of the form

$$Q_C = 460 f^{0.4}.$$

The data used in this study span the frequency range of 0.75-10 Hz. In addition, this study found that the frequency-dependent Q_C values also varied as a function of lapse time t. The lapse time is the time difference between the origin time of the earthquake and the arrival time of the coda wave at the seismometer. For short lapse times ($t < 100$ s), the power law is given by

$$Q_C = 140 f^{0.95}$$

and for longer lapse times ($t > 100$ s), the power law is of the form

$$Q_C = 660 f^{0.4}.$$

Toksöz et al. (1988) studied scattering and attenuation mechanisms in the Earth's crust using a wide variety of data, including coda waves, Rg waves, strong motion data, and laboratory data. Their results indicate that scattering is strong in the crust of the northeastern United States and Canada, with a value for the seismic albedo B_0 in the range 0.8-0.9, where the seismic albedo is defined as

$$B_0 = \frac{Q_S^{-1}}{Q_I^{-1} + Q_S^{-1}},$$

where Q_I and Q_S are the intrinsic attenuation and scattering attenuation, respectively. In addition, results from the analysis of Rg waves indicate that attenuation is strongest in the upper 1-2 kilometers of the crust and decreases with depth. Analysis of coda waves indicates that coda Q_C gives results of the form

$$Q_C = Q_0 f^n,$$

with a high constant value for Q_0 ($500 \leq Q_0 \leq 2000$) and n in the range 0.2 – 0.9, consistent with the results of Pulli (1984). They attribute coda Q_C as the result of a frequency-dependent intrinsic attenuation mechanism caused by fluid flow in the shallow crust.

This study expands upon the work of Pulli (1984) and Toksöz et al. (1988) in two major aspects. First, there are substantially more seismic data available. Second, the Q_C values determined from single-scattering models and the attenuation results from analysis of Rg waves do not explicitly separate out the effects of scattering and intrinsic attenuation.

The Energy-Flux Model

Frankel and Wennerberg (1987) developed the energy-flux model of seismic coda to explain results obtained from finite-difference modeling of seismic wave propagation in media that contained both intrinsic attenuation and scattering caused by small-scale random heterogeneities in seismic velocity. The energy-flux model is based on simple physics, namely conservation of energy, where a balance is maintained between energy scattered from the direct wave and energy transferred to the seismic coda. The model results in a simple formula that expresses the time-dependent seismic coda amplitude $A_C(t)$ as a function of angular frequency ω as well as the scattering Q_S^{-1} and the intrinsic (anelastic) attenuation Q_I^{-1},

$$A_C(t) = \sqrt{3I_D}\left(\frac{t_d}{t^{3/2}}\right)e^{-\omega t/(2Q_I)}e^{\omega t_d(1/Q_I+1/Q_S)/2}\sqrt{1-e^{-\omega t/Q_S}},$$

where t_d is the arrival time of the direct wave (i.e., the S-wave) and I_D is a measure of the energy in the direct wave observed at the receiver and is given by

$$I_D = \int_{t_1}^{t_2} A_D^2(t)dt,$$

where $A_D(t)$ is the amplitude of the direct wave and t_1 and t_2 are the limits of the time window used to bracket the direct wave arrival on the seismogram.

There are several attributes of the energy-flux model that make it applicable to the study of seismic wave scattering and attenuation. First, the model separates the effects of scattering and intrinsic attenuation, which allows for the estimation of the relative contribution of these mechanisms. This is a limitation of the single-scattering approach, because single-scattering models are formulated in terms of a single attenuation parameter, the coda Q_C. In fact, there has been much debate regarding the interpretation of Q_C. For example, Aki (1980) has argued that the coda amplitude is dependent on the amount of scattering in the medium. However, Frankel and Wennerberg (1987) have shown that the amplitude of the coda wave is actually sensitive to the intrinsic attenuation, and that the scattering is controlled primarily by the amount of energy transferred from the direct arrival (i.e., the S-wave) to the coda.

Second, the energy-flux model is valid for both weak and strong scattering, and it implicitly incorporates the effect of multiple scattering. Again, this is an advantage over single-scattering models, which use the Born approximation and explicitly neglect multiple scattering.

Finally, the model uses relative amplitudes, i.e., Q_I^{-1} and Q_S^{-1} depend on the amplitude of the seismic coda $A_C(t)$ relative to the amplitude of the direct wave $A_D(t)$. This is especially critical for this study because instrument calibration data are not available for the seismic instruments used in this study, making the determination of absolute amplitudes impossible.

The New England Seismic Network

The New England Seismic Network is operated by the Earth Resources Laboratory of the Department of Earth, Atmospheric, and Planetary Sciences of the Massachusetts Institute of Technology. The data used in this study were recorded by the network during a 15-year period from 1981 through 1995. During this time period, the network detected 182 earthquakes from which we were able to obtain nearly 600 usable seismograms for analysis. A map showing the locations of the seismic stations and the epicenters of the earthquakes is given in Figure 2.

The seismometers used by the network during the above-mentioned time period were short-period, vertical-component instruments with a nominal frequency response of 1 Hz. Within the frequency band of interest for this study (1-20 Hz), the response spectrum is essentially flat. The data were recorded continuously in an analog format and transmitted via dedicated telephone lines to a central processing facility, where the data were digitized at a rate of 50 samples per second and recorded in digital format using the SAC2000 software package (Goldstein et al., 2003). The data therefore have a Nyquist frequency of 25 Hz and we decided to limit the analyses of the data up to a maximum frequency of 20 Hz, or about 80% of the Nyquist frequency.

Estimation of Scattering and Intrinsic Attenuation

The energy-flux model is used to estimate the path-averaged scattering (Q_S^{-1}) and intrinsic attenuation (Q_I^{-1}) for the northeastern United States and adjacent Canada using seismograms recorded by MIT's New England Seismic Network. A nonlinear inversion scheme is developed whereby the energy-flux model is fit to the bandpass-filtered envelope of the seismic coda to estimate Q_S^{-1} and Q_I^{-1}. This inversion is performed at discrete frequency points over the frequency range 1-20 Hz in increments of 1 Hz. Each seismogram is filtered using a four-pole Butterworth digital filter centered on the frequency of interest. A logarithmic parameterization of the model parameters Q_S^{-1} and Q_I^{-1} is used to ensure that the model parameters estimated from the inversion have positive values (negative values for Q_S^{-1} and Q_I^{-1} would be physically meaningless).

From a practical standpoint, the most difficult aspect of the analysis, and the source of the largest potential errors in the results, is the estimation of the duration of the direct phase (i.e., the duration of the S-wave). It was found that the direct phase was difficult to isolate visually on the seismogram, given the intensity of the scattered waves present in the early part of the seismic coda. Therefore, it was necessary to develop a consistent methodology to provide a measure of the direct-wave duration.

The technique developed for this utilized the relationship between the source time function duration and the magnitude of the earthquake. The source time function is a measure of the temporal release of seismic energy during an earthquake, so that it provides a measure of the rupture duration of the earthquake. In general, the source time function duration increases with increasing magnitude. The source time function duration should therefore provide a good estimate of the duration of the direct phase.

We use the data of Li et al. (1995) and Feng and Ebel (1996) to develop a quantitative relationship between source time function duration and magnitude. Li et al. (1995) use the empirical Green's function technique to determine source time function duration for earthquakes from several different regions. Feng and Ebel (1996) use the pulse duration matching technique to determine rupture duration for twelve earthquakes in New England.

A plot of the logarithm of the source time function duration vs. magnitude (Figure 3) reveals a general linear relationship between the variables. A regression technique is used to determine the equation of the best fit line to the data. In addition, the 95% confidence bounds for the linear regression fit are determined (e.g., Draper and Smith, 1981). The best-fit line and 95% confidence bounds are plotted with the data in Figure 3.

Additionally, the direct-phase duration observed on the seismograms will be affected by the impulse response of the seismometers. The impulse response for the seismometers has a duration of approximately three seconds (Doll, 1988). We account for this by adding three seconds to the duration estimates derived from the regression equation to account for the "stretching out" of the observed direct-phase duration as a result of the convolution of the actual ground motion with the instrument response.

Sample inversion results (Figures 4 and Figure 5) are shown for two seismograms recorded from an earthquake that occurred on January 23, 1990 in northeastern Massachusetts. Figure 4 shows the recorded seismogram and inversion results for station WFM at an epicentral distance of 6 kilometers from the earthquake. The results indicate that scattering is strong and intrinsic attenuation is negligible. Figure 5 shows the recorded seismogram and inversion results from station COD for the same earthquake, recorded at an epicentral distance of 148 kilometers. These results are different than those from station WFM, namely, the scattering is significantly weaker and the intrinsic attenuation contributes a larger fraction to the overall energy loss. The error bars represent the 95% confidence bounds on the estimates of the path-averaged values of Q_S^{-1} and Q_I^{-1}, incorporating the uncertainties in the direct-phase duration estimates and the effect of the impulse response of the seismometers.

Additionally, the inversion results show a strong frequency dependence of both Q_S^{-1} and Q_I^{-1}. These results are consistent with the power-law relationship for coda Q_C from the single-scattering model used by Pulli (1984) and Toksöz et al. (1988), but the contributions of scattering and intrinsic attenuation are separated out.

Because of the nonlinearity of the energy-flux model, the inversion itself is nonlinear and it is therefore important to ensure that the solution obtained from the inversion is indeed the global solution and not a local solution from the multiple minima in the nonlinear solution space. To test this, we varied the initial model over a wide range of physically realistic models. In all cases, the inversion converged to the same solution, providing confidence that the solution is indeed the global solution.

The results shown in Figures 4 and 5 would indicate that scattering decreases with increasing epicentral distance and that intrinsic attenuation increases with increasing epicentral distance. We decided to examine all of the inversion results to see if there was a consistent variation of the path-averaged values of as Q_S^{-1} and Q_I^{-1}a function of epicentral distance. These data are plotted in Figure 6. The results show that scattering is indeed strongest at small epicentral distances and decreases rapidly as the epicentral distance increases, and appears to reach a nearly-constant value at large epicentral distances. The trend for the intrinsic attenuation is not as evident, but it appears to be negligible at small epicentral distances and increases at larger epicentral distances, although not as rapidly as the decrease in scattering.

At first glance, these results seem to be counterintuitive, especially with regard to scattering. If we assume that scatterers are homogeneously distributed in the Earth's crust, then we would expect to see an increase in scattering as the epicentral distance increases, because we would expect the seismic waves to encounter more scatterers the farther they propagate.

One way to explain these results is to assume that the Earth's crust is not homogeneous with respect to scattering, but that the distribution of scatterers is depth-dependent, with the number of scatterers decreasing with depth. Therefore, paths that travel over short epicentral distances would be confined to the shallowest part of the crust, and would experience more scattering in a path-averaged sense. This interpretation is consistent with the results of Toksöz et al. (1988), who found a strong depth dependence of attenuation from the inversion of Rg amplitude data.

Depth Dependence of Scattering and Intrinsic Attenuation

In order to investigate the hypothesis that scattering and intrinsic attenuation are depth dependent, we must make certain assumptions. First, there is an inherent inconsistency regarding the use of the energy-flux model. This model assumes that the scattering process is homogeneous in the Earth's crust, whereas we are now assuming that this is not the case, and that scattering actually depends on depth in the Earth's crust. However, we will assume that the energy-flux model is still valid for the analysis. Second, we will assume that the scattered energy observed in the seismic coda is localized near the raypath of the arriving seismic waves. This will allow us to use a simple ray-tracing algorithm to model the path-dependent scattering and intrinsic attenuation.

Given these assumptions, we can write equations for the path-averaged values of scattering $\overline{Q}_S^{-1}$ and intrinsic attenuation $\overline{Q}_I^{-1}$ of the form

$$\overline{Q}_S^{-1} = \frac{1}{T} \int_{raypath} Q_S^{-1}(z)dt,$$

and

$$\overline{Q}_I^{-1} = \frac{1}{T} \int_{raypath} Q_I^{-1}(z)dt,$$

where $Q_S^{-1}(z)$ and $Q_I^{-1}(z)$ are the depth-dependent functions of the scattering and intrinsic attenuation, respectively, T is the total travel time of the seismic wave, and the integral is taken over the raypath of the seismic wave. These equations are Fredholm integral equations of the first kind, and equations of this type are notoriously ill-conditioned (e.g., Press et al., 1992), i.e., the unknown functions $Q_S^{-1}(z)$ and $Q_I^{-1}(z)$ will be extremely sensitive to small changes in the observations $\overline{Q}_S^{-1}$ and $\overline{Q}_I^{-1}$. We can convert these integral equations into matrix equations by discretizing $Q_S^{-1}(z)$ and $Q_I^{-1}(z)$, which gives us matrix equations of the form

$$Gm_S = q_S,$$

and

$$Gm_I = q_I,$$

where G is a matrix whose rows contain the weighted travel time of the seismic wave in each layer, m_S and m_I are vectors whose elements contain the unknown values of the scattering Q_S^{-1} and intrinsic attenuation Q_I^{-1} in each layer, and q_S and q_I are vectors whose elements contain the values of the path-averaged scattering $\overline{Q}_S^{-1}$ and intrinsic attenuation $\overline{Q}_I^{-1}$ for each seismogram.

A simple inversion scheme is developed that uses these matrix equations to solve for the depth-dependent scattering and intrinsic attenuation. The depth-dependent functions are discretized into layers that are one kilometer thick. The number of observations is greater than the number of layers in the model, so the system of equations is overdetermined and can be solved in a least-squares sense. The least-squares solution of the matrix equations can be expressed in the form

$$m_S = (G^T G)^{-1} G^T q_S,$$

and

$$m_I = (G^T G)^{-1} G^T q_I,$$

where the matrix G^T represents the transpose of the matrix G. However, the inherent ill-conditioning of the Fredholm integral equation is also present in the matrix equations. Therefore, in order to obtain a solution, some form of regularization is needed to stabilize the inversion.

We choose to apply the Tikhonov regularization method (e.g., Groetsch, 1984) to stabilize the matrix inversions. This technique involves adding a damping term to the matrix inverse operation so that the least-squares solutions can now be written in the form

$$m_S = (G^T G + \tau R^T R)^{-1} G^T q_S,$$

and

$$m_I = (G^T G + \tau R^T R)^{-1} G^T q_I,$$

where τ is a damping parameter and R is a matrix that represents the discretization of the first-derivative operator. The Tikhonov regularization method allows us to obtain a smooth, stable solution to the least-squares problem.

The solution for the depth-dependent scattering and intrinsic attenuation structure is shown in Figure 7. The least-squares inversion is implemented using the nonlinear least squares algorithm (NNLS) of Lawson and Hanson (1974), again to ensure that the model parameters have positive values. We used the S-wave velocity model of Taylor and Toksöz (1982) for the ray tracing. This model was developed from the inversion of surface-wave group and phase velocity curves.

The results show that scattering is strongest at the shallowest part of the Earth's crust and decreases rapidly in the first few kilometers of depth. These results are consistent with those of Toksöz et al. (1988). In addition, the intrinsic attenuation is negligible near the Earth's surface and increases in the lower crust, where the value appears to decrease again near the crust-mantle boundary (Moho). Given the short epicentral distances of the seismograms used in this study, we can only resolve the scattering and attenuation structure down to a depth of about 48 kilometers, just below the Moho. Therefore, it is difficult to assess whether the decrease in intrinsic attenuation observed near the Moho is real or whether it is simply an artifact of the lack of data below that depth.

Discussion of Results

The results of this study would indicate that the scattering process in the Earth's crust in northeastern North America is confined to the shallowest depths. It is therefore useful to consider different geological conditions that may explain these results. The first is the presence of a surface layer of heterogeneous material with the size of the heterogeneities approximately equal to the wavelengths of the seismic coda. In fact, glacial till is pervasive in this area. However, it is unlikely that this contributes significantly to the scattering, since the glacial till cover is sporadic and the sizes of even the largest heterogeneities are much smaller that the wavelengths of the highest-frequency coda used in this study.

It may be possible to assess the importance of a surface layer to the scattering process by looking for reverberations. Such a study has been conducted by Jemberie and Langston (2005), who used the energy-flux model to estimate scattering and intrinsic attenuation from seismic data in the Mississippi embayment using broadband, three-component data from the Cooperative New Madrid Seismic Network. In their study, stations within the Mississippi embayment showed strong site-amplification effects at low frequencies (0.5 Hz and 1 Hz) on the horizontal components (both radial and tranverse) of recorded seismograms. The site amplifications were less evident on the vertical component. They attributed the site amplification to reverberations within the thick (up to 900 meters) sediments of the embayment. A similar study could be conducted for the New England region to see if site amplification effects may be present, and if these effects could be the result of significant thicknesses of glacial till. However, since the site amplification is most evident on the horizontal-component seismograms in the Mississippi embayment study, it may be difficult to observe the effect in this study, since only vertical-component seismograms are available.

A second scenario is the presence of fractures in the shallowest part of the Earth's crust. Such fractures could provide a significant heterogeneous medium in the shallow crust and their influence to the scattering process would decrease with increasing depth as the overburden pressure in the Earth caused the fractures to be closed at greater depths. In fact, Toksöz et al. (1988) attribute the attenuation observed in the inversion of Rg wave to the presence of fractures in the shallow crust. They attribute the attenuation to an intrinsic mechanism caused by fluid flow in the fractures. However, their analysis did not separate the effects of intrinsic attenuation from scattering.

A third scenario is that the scattering is cause by the presence of topography. Numerical modeling of seismic wave propagation (e.g. Hestholm and Ruud, 1998) and ultrasonic modeling (e.g., van Wijk et al., 2004) have shown that strong scattering occurs in the presence of surface topography. In the case of the ultrasonic modeling, as much as 90% of the seismic energy was scattered by a surface groove in an aluminum block. For the NESN earthquake data of this study, assuming an S-wave velocity of about 3.5 km/s at the surface, the longest wavelength in the seismic data (at 1 Hz) would be about 3.5 km. Since the strongest scattering is observed at this lower end of the frequency spectrum of the data, it would be expected that the dominant wavelength of the local topography should be of approximately this magnitude. Further study could focus on characterizing the wavelength spectrum of the topography to verify if the dominant wavelength in the topography is consistent with the scattering results.

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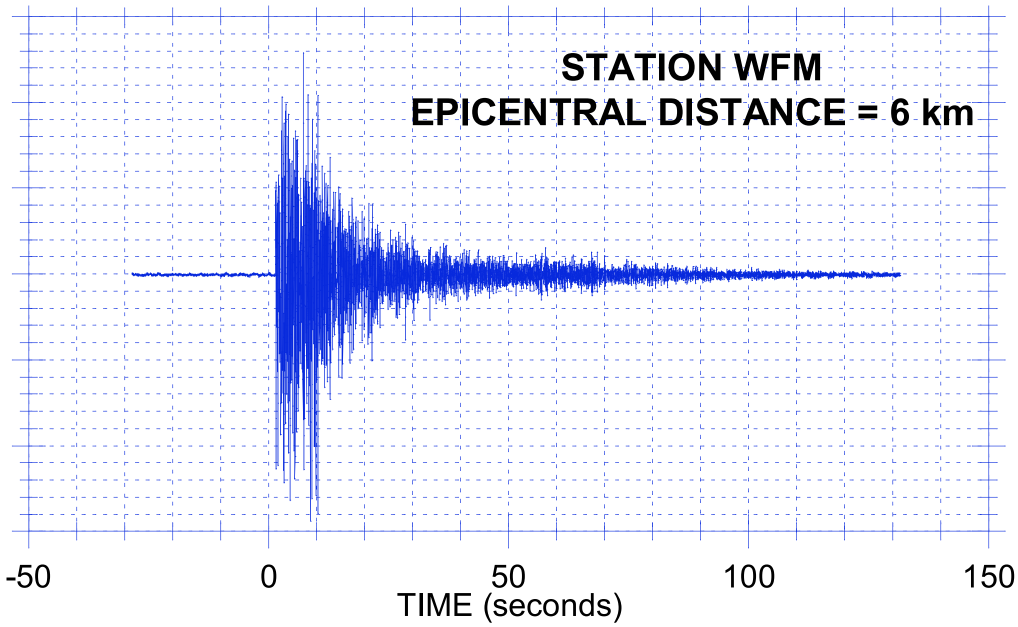


Figure 1. Sample seismogram from the New England Seismic Network. The seismogram was recorded on station WFM on January 23, 1990 from a M3.0 earthquake at an epicentral distance of 6 kilometers. The seismogram shows a well-developed seismic coda with its characteristic exponential decay as a function of lapse time.

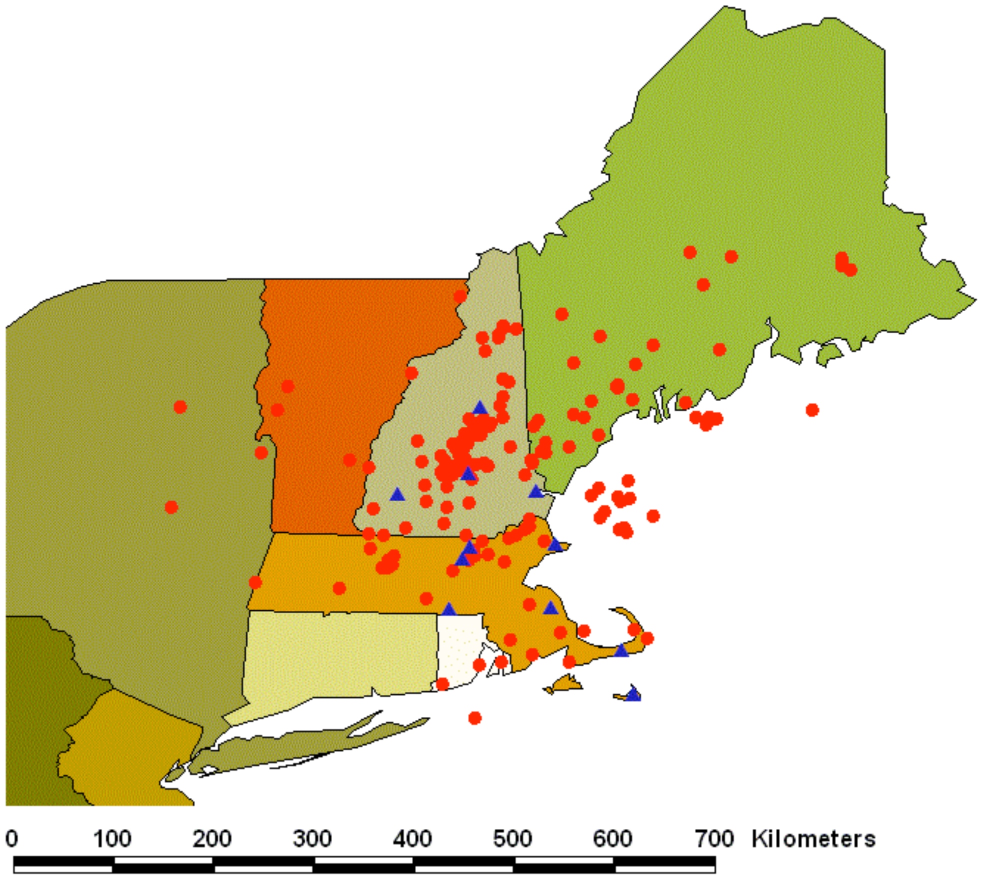


Figure 2. Map of the northeastern United States showing the locations of the stations (blue triangles) of the New England Seismic Network (NESN) and the earthquakes (red circles) recorded during 1981-1995.

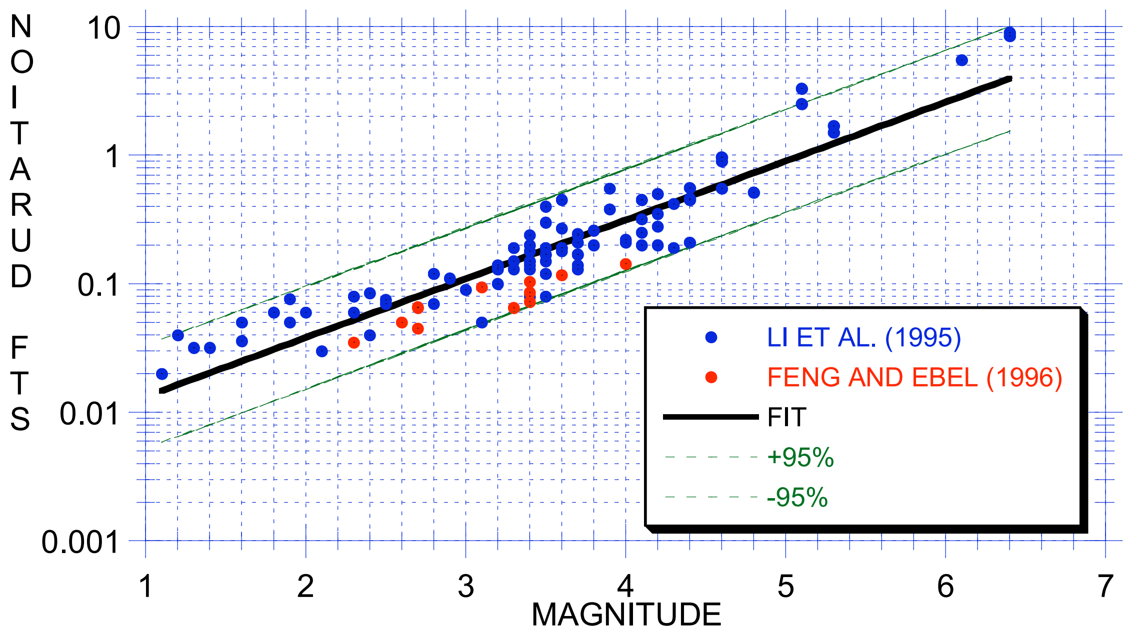
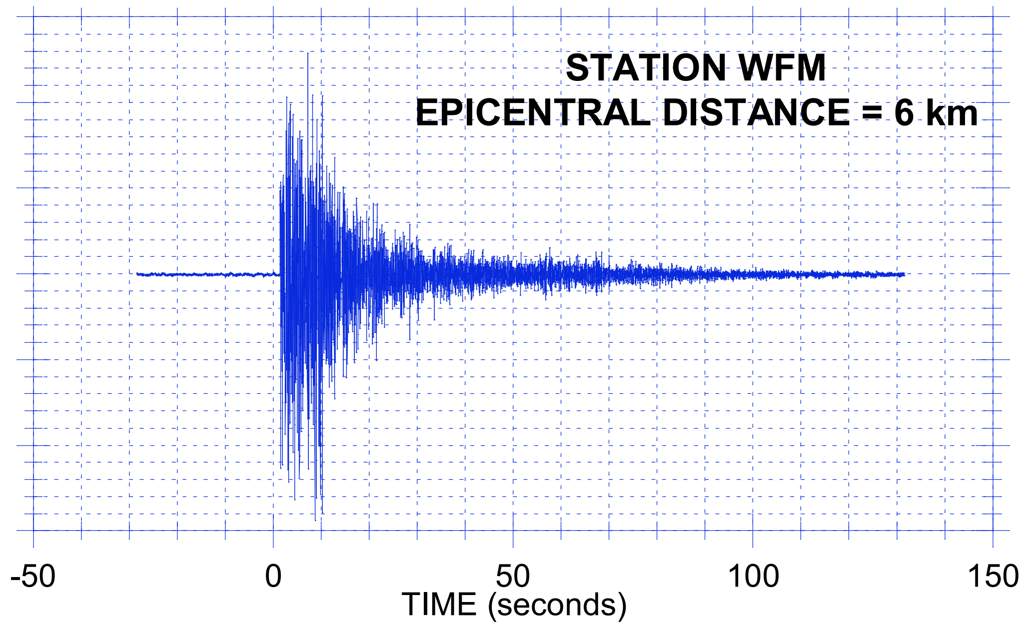


Figure 3. Source time function duration vs. magnitude for earthquakes. Data are from Li et al. (1995) and Feng and Ebel (1996). The solid line represents the straight-line fit to the data, and the dashed lines represent the 95% confidence bounds for the fit. The source time function duration is used in this study to estimate the duration of the direct S-wave.



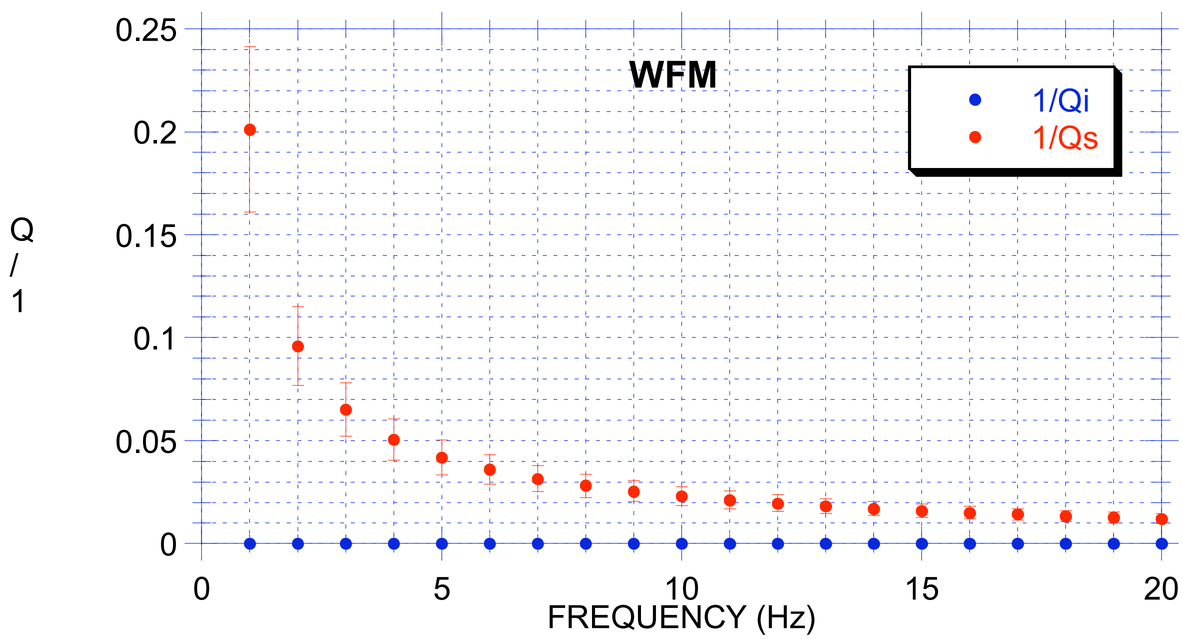


Figure 4. Inversion results for the seismogram from station WFM from an earthquake recorded on January 23, 1990 (M=3.0). The energy-flux model has been fit to the filtered envelope of the seismic coda decay at discrete frequencies from 1 Hz to 20 Hz. Station WFM is close to the earthquake and shows strong scattering and negligible intrinsic attenuation.

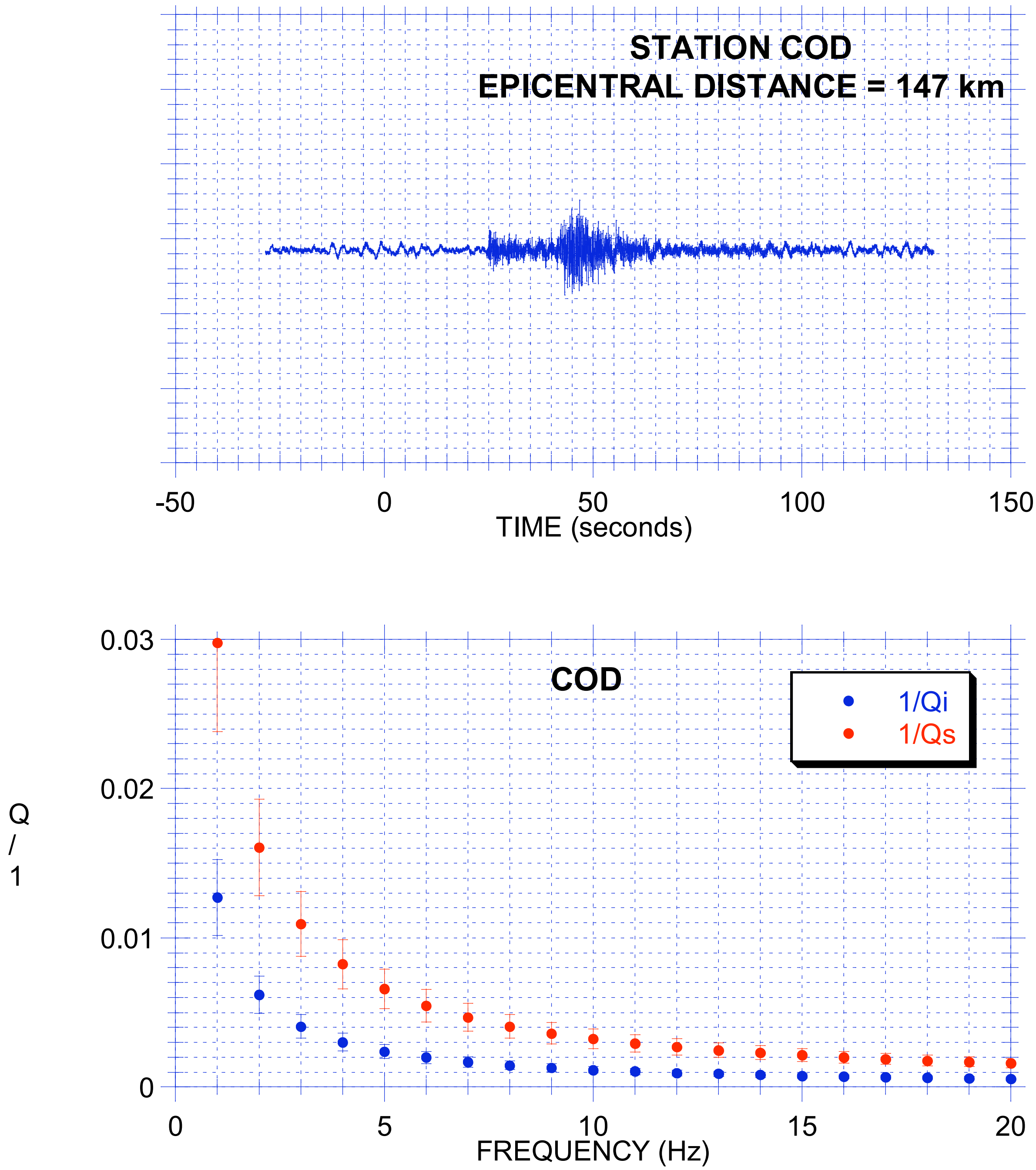


Figure 5. Inversion results for the seismogram from station COD from an earthquake recorded on January 23, 1990 (M=3.0). The energy-flux model has been fit to the filtered envelope of the seismic coda decay at discrete frequencies from 1 Hz to 20 Hz. Station COD is farther from the earthquake and shows weaker scattering and stronger intrinsic attenuation.

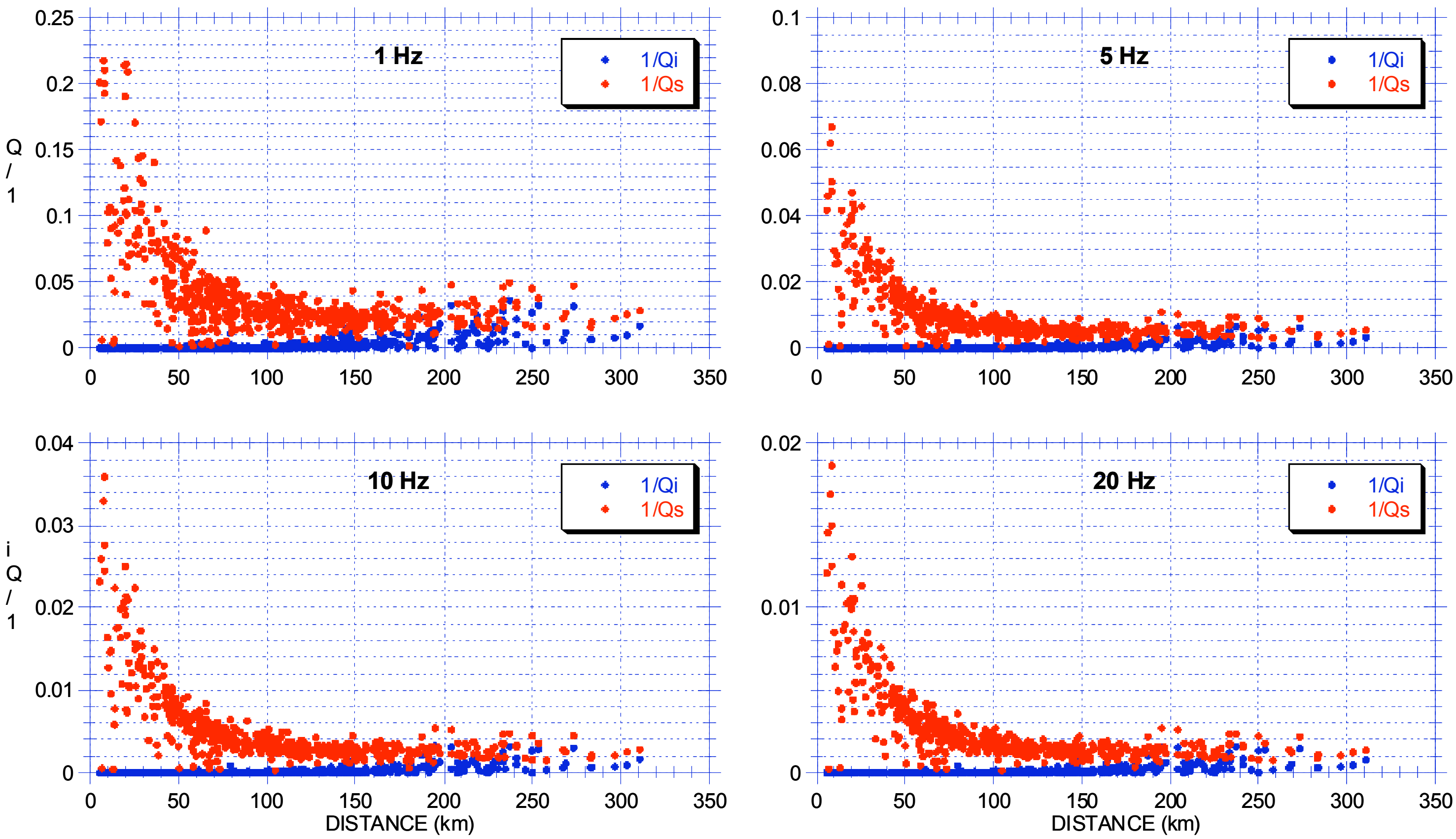


Figure 6. Plot of Q_I^{-1} and Q_S^{-1} as a function of epicentral distance for the frequencies 1 Hz, 5 Hz, 10 Hz, and 20 Hz. The strength of the scattering decreases markedly with distance, and the intrinsic attenuation increases with distance. We interpret these results as indicating a depth dependence to both Q_I^{-1} and Q_S^{-1}, where the shorter epicentral distances represent raypaths that sample the shallow part of the lithosphere and the longer epicentral distances represent raypaths that sample deeper into the lithosphere.

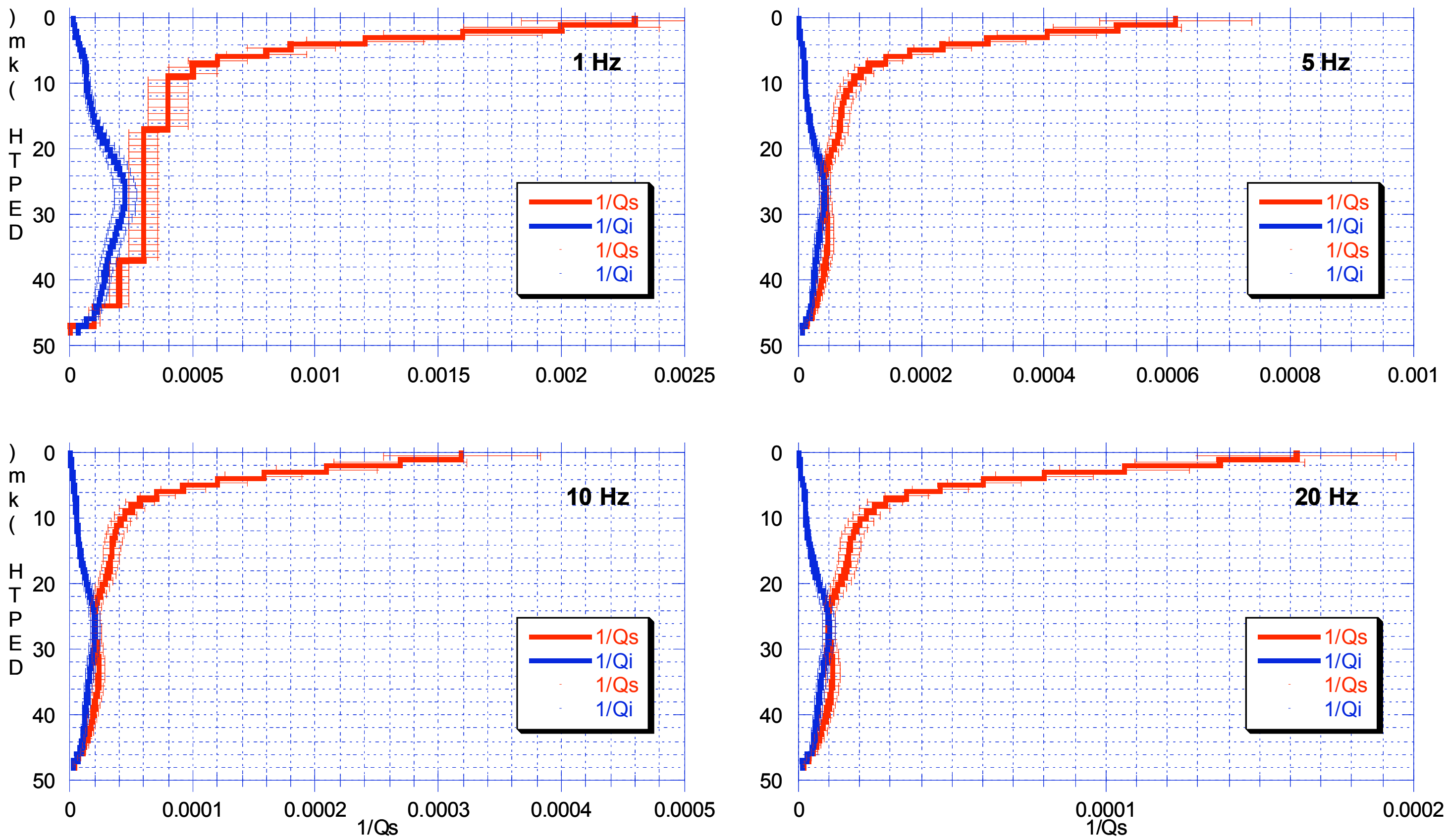


Figure 7. Inversion results for the 1-D depth structure of $Q_I^{-1}(z)$ and $Q_S^{-1}(z)$ for the frequencies 1 Hz, 5 Hz, 10 Hz, and 20 Hz. These results indicate that scattering is strongest at depths of only a few kilometers, and that intrinsic attenuation becomes stronger at greater depths. The error bars indicate the ± 95% confidence intervals for the inversion results.